SCIENCE FOCUS: Iron Fertilization

After the SOIREE: Testing the Limits of Iron Fertilization

"To Fe or not to Fe?"

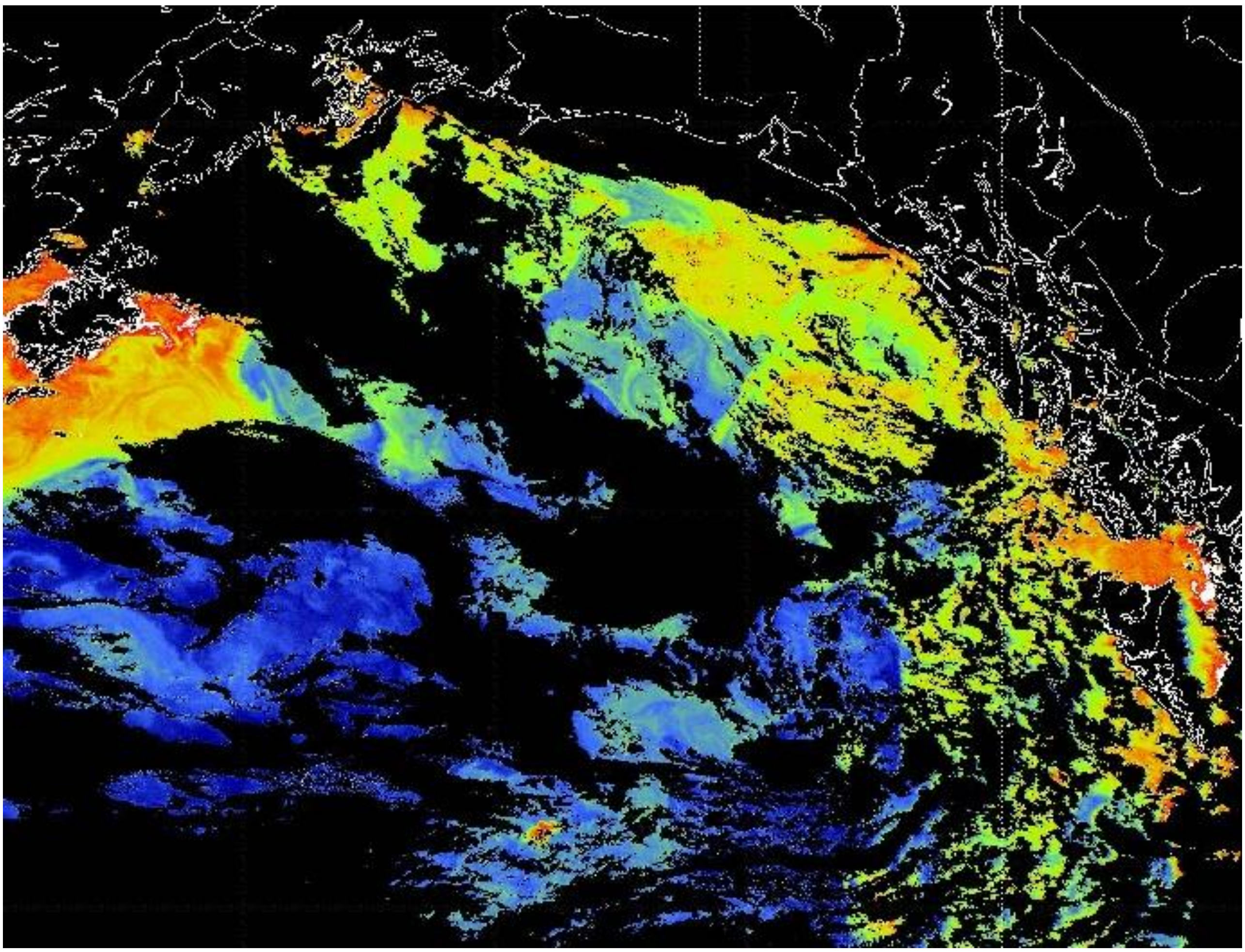
If that is the question, oceanographers have been seeking answers ever since the late John Martin proved that the element iron (Fe) is a limiting nutrient for the growth of phytoplankton in many regions of the ocean.

John Martin proposed it would be possible to add sufficient iron to the oceans to induce large phytoplankton blooms that would affect and reduce the rising concentration of carbon dioxide (CO_2) in Earth's atmosphere. Remove enough CO_2 from the atmosphere by this process, he surmised, and Earth's climate could even be affected (hence Martin's humorous comment that if you gave him a trainload of scrap iron, he'd give you another Ice Age).

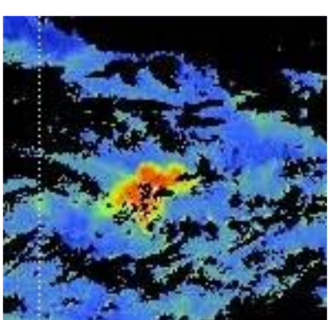
So, oceanographers have been seeking to determine if might be possible to do what Martin's jest suggested—in particular, they have been trying to answer the question of whether it is actually possible to reduce the concentration of CO_2 in the atmosphere by fertilizing the oceans with iron. If this were done on a sufficiently large scale, such a program would potentially cause the enhanced growth of phytoplankton, bigger and longer-lasting phytoplankton blooms, the accompanying extraction of CO_2 from the atmosphere, and—if the bloom sank into the ocean—this effort would ultimately result in the long-term sequestration of carbon derived from the atmosphere in the ocean depths.

Experiments such as Iron-Ex and SOIREE (see the *Science Focus!* article about SOIREE) showed that it was indeed possible to conduct large-scale ocean iron fertilization experiments. The recently-published results of two such experiments, SERIES (Subarctic Ecosystem Response to Iron Enrichment Study) and SOFeX (Southern Ocean Iron Experiment) have provided a range of answers to the prior question: one negative result and several results that might be positive.

The image below is a "lucky catch". SeaWiFS was fortunate to acquire two images of the SERIES iron-stimulated bloom in the cloudy northeastern Pacific Ocean (see Boyd *et al.* 2004). The image below was acquired on July 29, 2002, when the bloom was close to its peak, i.e., the concentration of phytoplankton was maximal as a result of previously rapid growth induced by the addition of iron. This image was acquired 19 days after the initial addition of iron to the surface ocean.



SeaWiFS image of the northeastern Pacific Ocean acquired on July 29, 2002, showing the SERIES iron-fertilized bloom at bottom center.



Close-up of SERIES iron-fertilized bloom.

SeaWiFS also acquired an image of the declining phase of the bloom five days later, when the growth of the phytoplankton had slowed down considerably. At this point, the bloom appears much "dimmer" because much of the bloom was no longer present in the upper ocean. The primary reason that the growth of phytoplankton slowed down between over those five days was the depletion of the important nutrients iron and silicic acid (which can be referred to as Si or silica). Without these nutrients, the phytoplankton couldn't continue to grow, and so the bloom declined, with only a small portion of the carbon it had produced sinking deep into the ocean.

The SERIES experiment results emphasized the importance of silica for the growth of the ubiquitous phytoplankton called **diatoms**. Diatoms form shells out of silica, and these shells come in an enormous variety of shapes and sizes. An example of a few different diatoms is shown below.

Photomicrograph of various diatom species.

Although SERIES produced a large amount of data for oceanographers to consider, two results were considered of primary importance. The first was the importance of silicic acid as a limiting nutrient for the continuing growth of diatoms and diatom blooms (see the section entitled "What is a limiting nutrient?" below). When iron was present in sufficient concentrations, the availability of silicic acid, used by the diatoms to make their shells, was the main control on the rate of diatom growth. When the added iron was used up, diatom growth was limited by both Fe and Si.

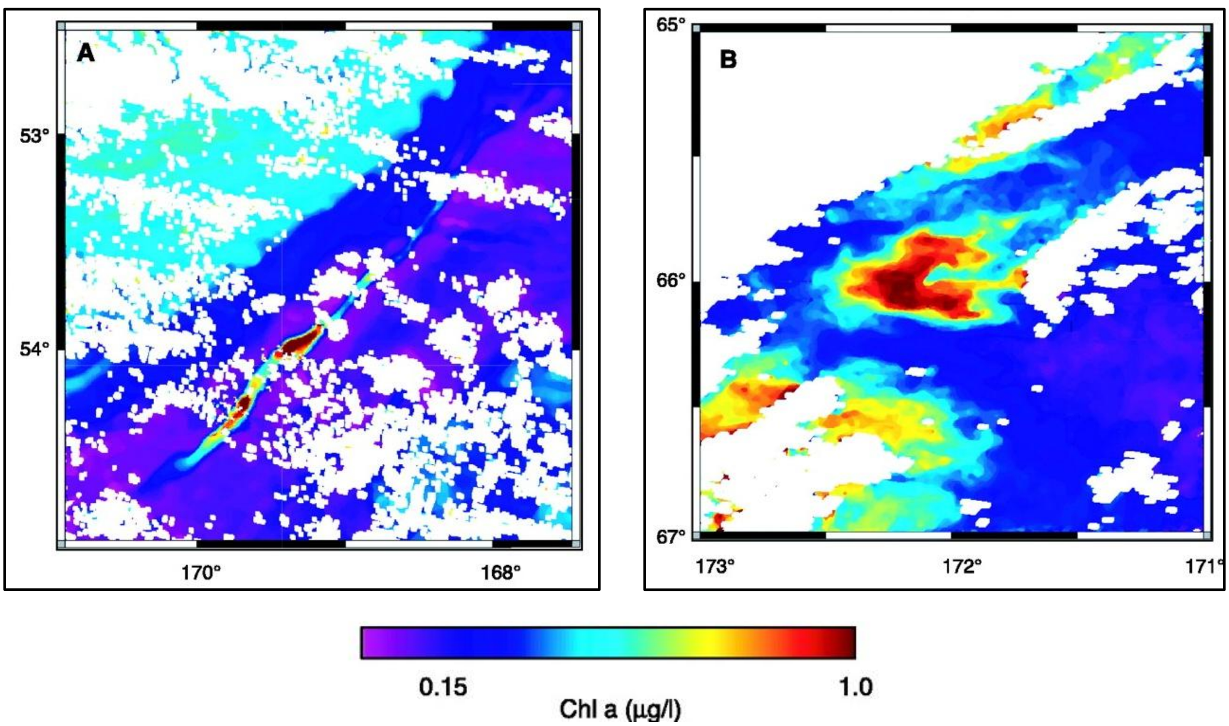
The second result concerned the rate of particulate organic carbon export from the bloom. Carbon export is important because the transfer of carbon from surface waters to the deep ocean is how iron fertilization would ultimately alter the concentration of atmospheric CO_2. Growing diatoms are subject to a variety of fates; one of the most common fates is that they are eaten by zooplankton.

The zooplankton excrete fecal material, which then sinks, which is an important mode of carbon export. However, if the zooplankton keep living near the surface of the ocean, getting bigger and fatter from feasting on diatoms, that's not a form of carbon export! Another diatom fate is that they simply die and sink, which is an export mode. A third fate is that they die and the organic matter they contain is digested (oceanographers use the term "re-mineralized") by bacteria. Because re-mineralized carbon from the diatoms also stays near the surface, this is also not a form of carbon export.

In the SERIES experiment, only a very small amount of organic carbon created by the growth of the diatoms was actually exported (traps for settling material deployed underneath the bloom were used to measure how much of the carbon sank into the deep ocean). So the SERIES results indicated that iron fertilization for the reduction of atmospheric CO_2 would not work, especially if there wasn't enough silicic acid to allow the continuing growth of diatoms.

But what if types of phytoplankton other than diatoms could utilize added iron to fuel their growth and reproduction? The results of SOFeX addressed that question.

SOFeX was conducted in two different locations in the Southern Ocean (the ocean around Antarctica). In the southern location, SOFeX-S, silicic acid concentrations are very high. In the northern location, SOFeX-N, silicic acid concentrations are very low. The following images are MODIS and SeaWiFS images of the SOFeX-N and SoFeX-S blooms, respectively. The images are excerpted with permission from Coale et al., "Southern Ocean Iron Enrichment Experiment: Carbon Cycling in High- and Low-Si Waters," *Science*, Vol. 304, Issue 5669, 408-414, 16 April 2004. [DOI: 10.1126/science.1089778] Copyright 2004 AAAS.



(left) MODIS image of the SOFeX-N northern iron-fertilized bloom. This image was acquired on day 28 of the experiment. (right) SeaWiFS image of the SOFeX-S southern iron-fertilized bloom. This image was acquired on day 20 of the experiment.

SoFeX-S produced a phytoplankton bloom consistent with expectations: a bloom consisting primarily of diatoms. Due to the high concentration of silicic acid and sufficient iron, this bloom kept on blooming and blooming—it was still "healthy" when the research vessel monitoring it had to return to port. As the diatoms were still healthy, not many of them died and sank to deeper waters, to the carbon flux exported from the bloom (measured by instrumented traps deployed beneath the bloom) was underestimated. And because the bloom consisted of diatoms, chemical measurements indicated that the bloom substantially depleted the available silicic acid in the waters where the bloom was active.

SoFeX-N produced a bloom that was somewhat more unusual. Rather than being composed primarily of diatoms, this bloom was a mixture of about 50% diatoms and 50% phytoplankton that did not make shells out of silica. This unusual bloom composition was one of the most significant results of SoFeX. The MODIS image indicates (by the shape of the bloom) that it was in an area with an oceanic front, and the circulation at the front carried part of the bloom down to deeper waters (a process called *subduction)*. Subduction of the bloom meant that more carbon was transferred to deeper waters than the simple sinking of carbon particles would have accomplished. Another significant result was that this bloom also showed no signs of slowing down when the experiment was over when ships had left the sites of the blooms. Free-drifting robotic buoys that measured seawater carbon chemistry were deployed in each bloom (Bishop *et al.* 2004), and these buoys continued to report back on the status of the bloom.

An important result from both SERIES and SoFeX was that the carbon export measurements were still considerably lower than estimates which have been used to model the use of oceanic iron fertilization for the purpose of removing CO_2 from the atmosphere. So even though the SERIES results indicated that iron fertilization was unlikely to appreciably affect atmospheric CO_2 concentrations, and the SoFeX results were more promising, iron fertilization is probably not an effective strategy to significantly alter CO_2 in the atmosphere.

At the end of 2004, an experiment named CROZEX investigated how iron from the Crozet Islands creates a persistent phytoplankton bloom in that region of the far southern Indian Ocean. The KEOPS study involved several cruises investigating how the Kerguelen archipelago couldprovide iron to the ocean waters in that region. The *Science Focus* article "The Low Zone" also discusses phytoplankton productivity, or the lack of it, in this region of the world.

What is a *limiting nutrient*?

One of the concepts central to the investigation of iron fertilization in the oceans is the concept of a *limiting nutrient*. Put simply, the limiting nutrient is the nutrient, an element required for phytoplankton growth, that is in shortest supply relative to the needs of the phytoplankton. The limiting nutrient will be the element that is used up by the growing phytoplankton first, and when the nutrient is used up, phytoplankton will cease growing.

While that concept may be simple, in the oceans it is not always easy to determine which nutrient is the limiting nutrient. The most common nutrients are nitrate (N) and phosphorus (P), and because marine organisms need a lot more N than P, nitrate is frequently the limiting nutrient, particularly in coastal areas. N is usually available to organisms in the form of dissolved nitrate ion, but ammonia and urea may also be utilized. Complicating the situation is the activity of phytoplankton, notably *Trichodesmium*, which can fix N from the atmosphere (as soybeans do on land) and act as a source of N for other phytoplankton.

As noted in the article, in the SERIES experiment, silicic acid became the limiting nutrient because diatoms require silicic acid to manufacture their ornate shells. However, the focus of the iron fertilization experiments has been on what are called high-nitrate low-chlorophyll (HNLC) regions of the ocean, where it is obvious that nitrate is not the limiting nutrient. The initiation of phytoplankton blooms by the addition of iron in HNLC regions confirmed that iron is the limiting nutrient in most of these areas.

Acknowledgments
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See also:
Science Focus! articles:
- SOIREE: A Phytoplankton Party in the Southern Ocean
- The Low Zone: A *Science Focus!* Inquiry Study

Subarctic Ecosystem Response to Iron Enrichment Study (SERIES): Eastern Subarctic Pacific, July 2002 (PDF)

Boyd et al.: "The decline and fate of an iron-induced subarctic phytoplankton bloom", *Nature*, Vol. 428, pages 549-553. (PDF)

Southern Ocean Iron Experiment (SoFeX) Cruise (SoFeX Home Page)

KEOPS—KErguelen: comparison study of the Ocean and Plateau in surface water

Trichodesmium

References

Note that these references are available online at *Science*, but require a subscription for access. The link after the reference will provide access to the article only if you have a subscription.

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